LCA Methodology

A Decision-Analytic Framework for Impact Assessment
Part 2: Midpoints, Endpoints, and Criteria for Method Development *

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Abstract. In the first part of this paper, we showed how life-cycle impact assessment can be described as an exercise in decision analysis. We developed a structure for how to decide on the relative importance of different environmental stressors. In this second part, we offer criteria for the grouping of stressors into impact categories and for the development of impact indicators. Facts to be included in a characterization method should be selected according to their relevance and combined following established scientific models. Facts should be included only if they are informative, that is, if sufficient and sufficiently certain information is available for all stressors that should be evaluated by this method. Abstract, constructed indicators at the 'midpoint level' are better suited to compare similar impacts than indicators reflecting 'observable environmental endpoints' if there is a large uncertainty about the effects on observable endpoints. We argue that midpoint modeling should be retained. The additional evidence introduced by endpoint methods should be used to support 'judgments about facts' needed to evaluate the importance of different impact categories (or means objectives) in the means-ends objectives network.

Introduction

Life-cycle impact assessment requires the comparative evaluation and aggregation of the various emissions, resources, and other disturbances such as land use and noise, connected to production, use, and disposal of a product. An aggregation of these 'stressors' invariably contains apples-and-oranges comparisons (Holdren et al. 1980). Stressors cause unlike effects to different people or ecosystems according to different mechanisms of action and at different times. Even if the mechanisms of action are the same, as for greenhouse gases, their dynamic behavior and therefore time horizon differs (Hertwich et al. 2000). The determination of the comparative detriment of one environmental insult relative to another is hence not primarily a question of measurement, it is one of judgment. The decision of how bad one insult is compared to others certainly depends on the scientific description of the resulting damage, but it also depends on our concerns, our attitudes towards uncertainty, and on whether damages are borne by those who obtain the benefits.

In the first part of this article, we have discussed how LCA impact assessment can be described and structured as a problem in decision analysis (Hertwich and Hammitt 2001).[1] Category indicators in LCA, such as the global warming potential, are called attributes in decision analysis. The prevention or minimization of the corresponding impacts, e.g. temperature increase and sea-level rise, is the related objective. Our investigation of the use of decision analysis to structure and justify impact assessment is motivated by the recognition that LCA can be defended as a rational tool only through its use in decision making, and not as a scientific measurement device. It is desirable to do LCA because it is the only decision support tool that allows for a comprehensive inclusion of environmental impacts throughout the product life as well as the systematic comparison of releases at different points and to different media (Hertwich et al. 2000). The development of generic impact assessment methods and a generally available public set of indicators is justified because it presents a clear improvement over the current situation where assessments are difficult or impossible. Given the anatomy of the decision making problem in LCA, characterized by the necessity of value judgments and the need for science to describe the relevant facts, we have derived criteria for objectivity which impact assessment methods should satisfy (Hertwich et al. 2000).

In the second part of this article, we investigate the issue of method choice in more detail. We are specifically interested in how decision analysis can help us discriminate among competing methods. There is a wide range of competing methods both in terms of the overall assessment approach and for single impact categories (Pennington et al. 2000). We distinguish methods that follow the *environmental themes* approach from those based on a *damage function* approach.[2] The *environmental themes* approach was defined

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[1] A similar approach has also been taken by Seppälä (1999).
[2] A recent UNEP workshop (Bare et al. 2000b) framed the discussion as 'midpoint' vs. 'endpoint'. Since there is no agreement among the participants as to which methods are midpoint or endpoint, we do not adopt this terminology. According to the pre-workshop material for the UNEP workshop (Bare et al. 2000b), endpoint modeling refers to assessment describing observable environmental endpoints, and midpoint modeling is assessment that stops short of describing observable endpoints. In the terms introduced in part 1, endpoint indicators are natural attributes at the end of the cause-consequence chain, such as years of life lost, whereas midpoint indicators are constructed attributes located somewhere along the cause-consequence chain, such as the global warming potential.
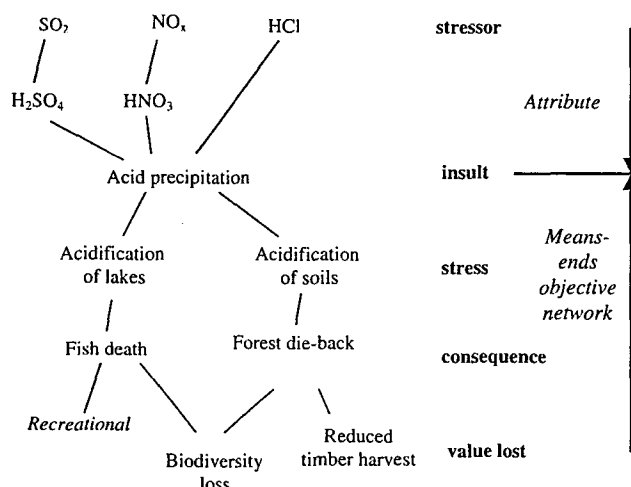
Fig. 1: Structuring of objectives and specification of attributes in life cycle impact assessment: Several impact chains can be grouped together because there is a common mechanism of action going from the insult to the value lost. The commonly used attribute for the acidification category – [H^+] loading or SO_2 equivalents – describes an insult; the remainder of the causal chain is then left to be evaluated by 'valuation.' It can be described by a means-ends objectives network

by the prominent CML-guide (Heijungs et al. 1992). It was adopted by the Society of Environmental Toxicology and Chemistry, SETAC (Fava et al. 1993) and in ISO 14042 (ISO 2000). Similar approaches have been used before, e.g. in the assessment of energy technologies (Holdren et al. 1980). In a first step, classification, stressors are grouped into separate impact 'categories' such as global warming or acidification (Fig. 1). In a second step, characterization, the relative contribution of stressors to each category is evaluated. In a third step, valuation or weighting, the importance of different impacts is evaluated. Alternatively or as a preparation for weighting, the category indicators can be normalized by dividing it by the characterized environmental stressors in a country, and/or grouped according to importance (Finnveden et al. 2001). The category indicators were chosen at the lowest level at which a commonality between the stressors in each category can be established, e.g. the infrared absorption capacity of greenhouse gases or the potential to donate H^+ ions for acidic compounds (Fig. 1).

Damage function modeling goes back to the economic evaluation of environmental damages and, to our knowledge, was first introduced to LCA through the Environmental Priority

System, EPS (Steen and Ryding 1991). It requires an assessment of the whole cause-effect chain described in the first part (Hertwich and Hammitt 2001, Fig. 1). Damage function methods, such as EPS (Steen 1999) and the Eco-Indicator 99 (Goedkoop and Spriensma 1999), do not follow the environmental themes approach; they attempt to predict damage and then aggregate predicted damages in terms of an indicator that already includes explicit valuation.

The decision-analytic structure described in the first part (Hertwich and Hammitt 2001), distinguishing between attributes (category indicators) and the trade-off of objectives (weighting), corresponds to the environmental themes approach. Table 1 compares the terminology used in our decision-analytic framework with that of LCA impact assessment. We will refine this structure further through the introduction of criteria for what we call the construction of attributes. We will first address the grouping of impacts into a limited number of categories. Then we will focus on the development of category indicators. In the last part, we will address the current midpoint vs. endpoint debate and discuss the strengths and weaknesses of the environmental themes and damage function approaches.

1 Establishment of Impact Categories

Following the environmental themes approach, Udo de Haes (1996) recommended a list of 14 impact categories, including land use, ozone depletion, ecosystem toxicity, and radiation. Such grouping of impact chains into impact categories is a matter of analytical convenience and heuristic necessity. There are too many stressors – each of which has multiple impact chains and affects different endpoints – to analyze each and every one of these chains. The limitations of human judgment are well documented and suggest that the number of factors that we can consider at any one time is very limited (Kleindorfer et al. 1993). Hence we are trying to find common attributes and objectives that allow us to group impacts.

The grouping of causal chains into impact categories is based on similarities among these chains. The ultimate requirement for the stressors in an impact category is that they all need to 'fit' the same characterization method. The example in Fig. 1 illustrates the causal chain of acidification. In this case, the impact category is selected because the same mecha-

Table 1: Relationship between the terminology suggested by decision analysis and traditional LCA terminology. Modified from Udo de Haes and Lindeijer (2001)

Terms used in decision analysis	Corresponding terms used in LCIA
attribute means-ends objective network fundamental objectives network	category indicator relationship of category indicators to endpoints relationship of endpoints to safeguard subjects
stressor insult stress consequence value lost	environmental intervention midpoint midpoint endpoint (damage)
structuring the assessment constructing attributes trade off among objectives (valuation)	categorization development of characterization methods weighting of category indicators

nism of action leads from the insult of acid precipitation to various consequences, independent of the stressor that causes acid precipitation.

The following criteria provide guidance for the grouping of impact chains into a single impact category:

1. The impact chains grouped into one category should be similar enough so that they can be described by the same pieces of information. Hence, a constructed attribute combining individual pieces of information should appropriately reflect the hazard of a stressor at a given depth – compared to other stressors in the same category. The grouping of impacts may be justified in terms of a similar mechanism of action, a similar endpoint, or the same tools by which we understand and analyze the impacts grouped in a category.

2. The impact category should capture the most important contributions of a certain stressor to the endpoint (value lost) that the category is meant to cover. For example, if we judge the direct effect of SO_2 on trees to be significant compared to the acidification caused by sulfuric acid then we need to find a way to include this effect. This may either be in a separate impact category (e.g., phytotoxicity) or through a change of the present category.

The first criterion is dictated by the requirement of technical validity. If the same pieces of information have a different meaning for different impacts chains (i.e., if different models need to be applied containing the same parameters) then the equivalent treatment of these pieces of information is incorrect. The second criterion arises from the desire to be comprehensive. If the most important impact chains are not covered by the assessment, the assessment will not appropriately reflect the issue of concern and hence will produce misleading results.

1.1 Grouping of toxic impacts

To early LCA practitioners it may have seemed to be an obvious choice to group all toxic effects in humans into a single category. This choice is not obvious to a risk assessor, much less to a toxicologist. Toxic chemicals act according to different mechanisms of action in different organs and result in different effects. Toxic chemicals may impact the portal of entry (lung, intestine, etc.) and then be rapidly detoxified, or they may be relatively harmless at the entry and require metabolic activation in the liver or the kidney. Toxicologists distinguish between local effects that focus on a single organ and systemic effects in the whole body. They distinguish among acute, repeated, and chronic exposure and among persistent, transient, cumulative, and latent effects. Chemicals may cause sensitization and allergic effects, they may affect a whole population or only those genetically predisposed. Toxic effects differ in their severity, their potential for medical treatment, and the age groups that are affected. Some have suggested that the same mechanism of action is required to group effects into a single category; this condition is clearly not fulfilled in the case of toxic effects. So why are they still grouped together?

Despite the dissimilar mechanisms of action and dissimilar effects of toxic chemicals, we have developed a single cognitive strategy to learn about these chemicals and to decide about preventive action. We recognize that, for an adverse effect to occur, a chemical needs to possess a property we call toxicity and that humans need to be exposed. Toxicology has developed a set of tools to assess toxicity. These include traditional tests like animal bioassays, in vitro tests, and epidemiological investigations. With the advent of molecular biology and biochemistry the set of tools has been greatly expanded. The most widely available and frequently used tests results, however, are still the effective or lethal dose measures in animal tests. Exposure analysis has developed measurement methods and models to assess whether individuals are or have been exposed to chemicals and to estimate the magnitude and duration of the exposure. Society has developed a uniform response mechanism to toxic chemicals; risk analysis combines the results of toxicology and exposure assessment to evaluate the magnitude of a risk, and risk management takes the appropriate action to mitigate risks that are deemed to be undesirable. Risk analysis and management have been adopted as response strategies in a wide set of laws and regulations that deal with issues ranging from food safety to air quality (NRC 1994). While most of these laws and regulations do not explicitly compare risks, the intent is to apply the same criteria and stringency to all the chemicals covered by a specific piece of legislation.

The justification for creating a category of human toxicity is that we use the same cognitive strategies and scientific tests to understand and evaluate toxic chemicals, in spite of their dissimilarities. We use the same pieces of information – dose-response relationship and exposure estimate – to assess the risk of a chemical and to decide about what to do.

2 The Construction of Attributes

The most interesting question in the methodological development of impact assessment may be how to *construct meaningful attributes*. Analogous to the issue of theory choice in the epistemology of science (Klee 1997, Hertwich et al. 2000), this question can also be phrased as one of method choice. Two issues arise in attribute construction: (1) what information should be included, and (2) how should this information be combined? Competing methods may differ in what information they include and how they combine it.

If the attribute is meant to describe at least part of an impact chain, it can be interpreted as a physical quantity. In many cases a scientific model describing physical or economic relationships will be the most suitable basis for attribute construction. Indeed, physical models have been used extensively in the development of LCA impact indicators. The global warming potential (GWP), for example, is based on models of the atmospheric fate of greenhouse gases and the radiation balance of the atmosphere. The GWP represents the time-integrated infrared absorption. The ozone depletion potential (ODP) is based on a model of atmospheric fate and chemistry describing ozone depletion in the stratosphere. The ODP represents the steady state decrease in stratospheric ozone resulting from a marginal increase in emissions of the ozone depleting gas (Wuebbles 1995).

Scientific models are attractive because they embody scientific knowledge about the relationship of the stressor to our concerns. They can be validated and improved according to established procedures, and they can serve as a rallying point for achieving agreement. Scientific models seem less arbitrary than the construction of more artificial indicators. We should keep in mind, however, that the purpose of the attribute is to reflect concerns, not to represent physical quantities. Indeed, the model parameterizations and conditions used for the development of indicators are often not 'realistic.' The GWP is based on a present-day atmosphere, it does not take into account the projected increase in greenhouse gas concentrations. In addition, some of the feedback mechanisms of increased greenhouse gas concentrations were neglected, resulting in significantly smaller GWPs for the non-CO_2 greenhouse gases (Wuebbles et al. 1995). The choice to ignore some mechanisms may have been driven by the desire to avoid basing the GWP on uncertain and therefore more easily contested information. Similarly, the use of steady-state conditions for the ODP does not reflect the expected situation. These choices reflect normative and epistemic judgments on part of the indicator developers, who see these simplified models as a more adequate basis for decision making.

Based on the previous discussion of LCA and decision analysis, we would like to offer a number of criteria for the construction of attributes. These criteria are meant to guide decisions about what kind of information to use in constructing attributes and how to combine this information.

1. Information must be meaningful to the problem. The data that are included in the attribute must have a relationship to the objective that the attribute is supposed to reflect. A basic scientific understanding of the problem is required to decide whether information is related to the objective. This criterion is most directly justified by Keeney's (1992) demand that the objective represented by the attribute should be essential. It is furthermore supported by requirements for analytical efficiency and technical validity. In ISO 14042, this criterion is termed 'environmental relevance.'
2. The combination of the information should reflect our understanding of the relationship between the stressor and the subject of concern. In many cases, a model describing a part of the cause-consequence chain will be used. Such models are based on an understanding of the physical relationship among different variables. The use of models is not required by decision analysis, but it reflects our desire to appropriately understand the relationship between stressors and impacts and to include this understanding in our assessment. This criterion hence helps to ensure normative relevance and technical validity. In addition, the physical interpretation potentially provides for a more understandable attribute, based on information and models that can be validated.
3. Analytical refinement must be informative: Additional data or analysis must be informative enough so that its value-of-information outweighs the higher costs of analysis. Sufficient data must be available and the available data must be certain enough to be informative about the attainment of the objective. The idea of 'informative-

ness' (Hammitt and Shlyakhter 1999) was inspired by value-of-information analysis (Morgan and Henrion 1990). Hertwich (1999) suggested a measure of 'resolution' serve as a test for this criterion.

This criterion suggests that information should only be included if it actually has the potential to influence a decision. This is in the interest of analytic efficiency and practicality. It is also supported by Keeney's call for including only 'essential' properties. In several cases, analysts have suggested to include pieces of information which may, in principle, be relevant to the problem but which are not available for most of the impact chains of concern. If data for part of the impact chain are not available and we have to use the same uncertainty distributions for most of the impact chains then the additional analysis or information clouds the picture; it does not contribute to our knowledge and can be omitted.

2.1 The appropriate depth of analysis

If scientific models are utilized in the construction of attributes, the question of what information should be included can be specified as: what is the appropriate depth of analysis, and what is the level of detail with which each step in the cause-consequence chain is described? As previously indicated, the *depth of analysis* expresses the level in the impact chain at which the means objective is located; elements up to this level are included in the calculation of the attribute.[3] A more detailed analysis should be able to give a more realistic picture of the potential environmental consequences because it includes more information. While this would argue in favor of an increased depth, the costs of analysis and the lack of information favor less depth.

The question of the appropriate depth of analysis frequently occurs in environmental policy analysis. The choice of analytical depth requires making tradeoffs between desired criteria, notably the relevance of the indicator (the extent to which it captures consequences that are of direct interest to policy makers) and the accuracy with which future levels of the indicator can be projected under alternative policies (Hammitt 1999). The comparison of alternative evaluations of climate change policy illustrates that the choice of the evaluation endpoint can have important implications for the choice of alternative policies. The standard evaluation endpoint for response strategies to climate change is the level at which CO_2 concentration is stabilized. If stabilization was the goal, emissions reductions could be postponed. Hammitt (1999) shows that if instead the maximization of the net benefits of emission control is the goal, an earlier reduction of greenhouse gas emissions is desirable. In other words, the largest net benefits can be obtained from a policy of early, gradual emissions control. The difference between evaluation endpoints parallels our comparison of the economic damage indicator (EDI) and the global warming Potential (Hertwich et al. 2000).

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[3] In the terminology of the UNEP workshop (Bare et al. 2000b), this could be rephrased as the question of how close to the ultimate, observable endpoint the category indicator should be.

The evaluation of acidifying substances in LCA provides another example. The standard assessment follows the simple scheme depicted in Fig. 1. Emissions are compared on the basis of the amount of hydrogen protons that they will generate. A more sophisticated method includes spatially dependent information on the buffering capacity of soils and surface waters onto which acid precipitation falls (Potting et al. 1998, Huijbregts 2000). With this site-specific assessment the differences among acid precursors are smaller than the differences among release sites.

In the cases of climate change and acidification, the more sophisticated analysis has introduced elements that affect not the primary insult but elements further down the impact chain. The compared chemicals do not differ in the physical mechanisms that lead to harm further down the chain, but in the timing and/or location of this harm. This influences mitigating factors, which can be physical or socioeconomic in nature.

The desired trade-off between the costs and benefits of an increased depth of analysis will depend on the resources and the purpose of the analysis in questions. A simple method should be available to serve as a default, but this should not prevent researchers from attempting a more detailed analysis if such an analysis is likely to produce different results.

The additional considerations introduced by Hammitt et al. (1996) and Potting et al. (1998) are clearly relevant and important for relating the different stressors to their consequences. These two cases suggest that a more detailed analysis can lead to significantly different conclusions. The cost of a more detailed analysis lies in the additional information required and the additional uncertainties introduced to the analysis. The economic damage indicator (Hammitt et al. 1996) requires more information for the development of the indicator than the global warming potential (Wuebbles et al. 1995). This information, however, is already collected for other policy purposes. The way it is included is based on the results of integrated assessment models, which are subject to peer review. The acidification potential suggested by Potting and colleagues (1998) requires additional information in the development and the use of the indicator. The development relies on the rigorously reviewed and tested RAINS model, which was developed to support treaty negotiations on acid precipitation in Europe. The requirement for release site information, however, raises the cost of applying the method. The availability of factors only for Europe limits the scope of application.

In the case of climate change, uncertainty increases with an increased depth of analysis (Hammitt 1999). The assessment of the consequences of climate change, such as the change in sea levels or the frequency of storms, is much more uncertain than the assessment of the increase in infrared radiation or the global average temperature. To what degree should this increase in uncertainty be accepted as a price for a higher relevance?

No clear guidelines exist for the tradeoff between the relevance and the reliability of an attribute. Our third criterion for the construction of meaningful attributes, however, constitutes a minimum requirement for the inclusion of particular steps of analysis. If we were not able to make informative statements about the relationship of the increase in infrared absorption to the consequences of climate change there would be no point in introducing these considerations into the tradeoff among different greenhouse gases. Since the EDI concerns the distinction of infrared absorption at different points in time, 'informative statements' are statements allowing to distinguish the magnitude of consequence depending on the timing of the stress. The marginal consequences of additional infrared absorption are expected to be worse at high greenhouse gas concentrations and under scenarios of a fast increase in temperature. Informative statements can hence be made about the functional relationship between stress and consequence.

3   Damage-Function Approaches

LCA impact assessment methods that are based on a modeling of consequences are becoming increasingly popular. The damage functions introduced by these methods to LCA are used in economics and medical decision analysis to evaluate different measures and alternatives. Similarities between life-cycle assessments and environmental economic assessments are most apparent in the case of energy technologies (Krewitt et al. 1999, Levy et al. 1999, Spadaro and Rabl 1999). The proponents of damage function approaches such as EPS (Steen 1999) and Eco-Indicator 99 (Goedkoop and Spriensma 1999) argue that these are superior and therefore a desirable replacement for the environmental themes approach.

The most clearly identified difference between damage function methods and the environmental themes approach lies in how valuation is integrated into the analysis. The environmental themes approach separates characterization and valuation. Category indicators are constructed attributes based on implicit value judgments about what is both relevant and sufficiently reliable to be included in the analysis. The meaning of these indicators has to be interpreted by those partaking in the valuation exercise. Damage modeling, on the other hand, uses explicit valuation results from studies outside LCA in the first indicator that is calculated by a user of the method. For human health, EPS calculates expected disease incidence and years of life lost (YOLL) and uses the value of a statistical life and other contingent valuation results to convert this into a monetary value. The Eco-Indicator 99 uses the concept of disability-adjusted life years (DALYs) to convert years of life lost and years lived at various degrees of disability into a common unit (Hofstetter 1998).

Damage modeling offers two advantages. One, it may be possible to compare the damage resulting from different impact categories. Human toxicants, photooxidants, ozone depletion, and global warming all threaten human health. If an endpoint analysis allows us to directly compare their effects in terms of a common yard stick such as Euros or DALYs, "we don't have to do these calculations in our head," as Goedkoop argued at the aforementioned UNEP workshop. Two, damage specified in years of life lost or monetary units is more concrete, more vivid, than abstract indicators such as "CO_2 equivalents" used in the thematic approach. It can be directly compared to other risks such as

car accidents or smoking. Being closer to our concerns, they form a more solid basis for valuation. This may be the reason why valuation results are readily available.

An assessment based on 'observable consequences', however, requires a prediction of the damages resulting from various stressors. A predicted damage, such as years of life lost, constitutes a factual truth claim. It should fulfil the requirement of scientific validity. Damage modeling makes much stronger truth claims and thus has to meet tougher standards of evidence than an evaluation following the environmental themes approach. Such requirements are necessary because damage modeling makes statements not only about the relative importance of stressors but also about their absolute scale, that is, their importance relative to health care, traffic safety, and education. The question is, given the complexity of environmental, physiological, and economic processes, can LCA deliver such scientifically valid predictions?

In our opinion, the scientific credibility of damage models can only be maintained if uncertainty is fully expressed and carried through in the analysis. Based on a Baysian statistical perspective, uncertainty distributions for dose-response relationships for chemicals lacking specific evidence can be based on data from chemicals that have such data. For cases such as climate change, for which no prior experience exists, the connection between insult and endpoint can based on expert judgment (Morgan and Keith 1995). In other words, data gaps can be replaced by highly uncertain data that represents the entire range of possible outcomes (Fig. 2). This is the only way in which we can assure that factual claims, such as the years of life lost due to an insult, remain valid.

If such a practice is established, the danger is that uncertainty swaps out all other information included in the analysis, so that no meaningful differences between alternatives investigated by LCA can ever be established. It is easier to establish a relative difference between two alternative than their absolute impact. Uncertainty about factors that are
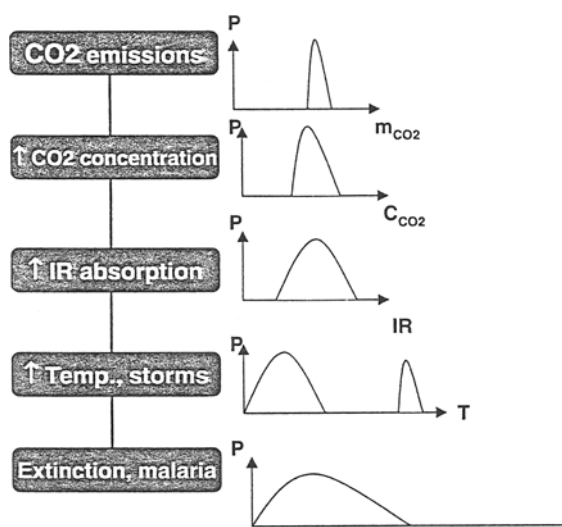
common to both will affect estimates of the absolute impacts much more than estimates of the relative impact, under reasonable assumptions. For example, if one factor like a dose-response slope enters the impact calculation for both technologies, error in the estimated coefficient will affect the estimated impact in a proportional way, but will not reverse any ranking between the technologies. Thus, a comparative LCA may yield inconclusive results even if there is a meaningful difference between alternatives. The hypothetical example in Fig. 3 illustrates such a case. In Fig. 3, the two life cycle inventories contain only two emissions each. One stressor each contributes to global warming, the other to human health. Assume that, using the global warming potential and the human toxicity potential (or any of their competitors), we find that LC1 is clearly worse than LC2. If we go directly to the endpoint, however, quantifying the large uncertainty about the human and ecological effects of climate change or toxic compounds, we find a large overlap between LC1 and LC2. LC1 will still be statistically dominant, but if we calculate the reliability of our conclusions following Steen (1997), it will be very low. How serious the problem of uncertainty and data gaps introduced in damage modeling is and how strongly it affects the reliability of LCA results remains to be investigated. While EPS, Eco-Indicator 99, and the ExternE project (European Commission 1999, Eyre et al. 1999) all contain data on the uncertainty of the effects, this data does not easily lend itself to such an investigation. Only part of the uncertainty is quantified, and the evaluations have significant data gaps.

In our search for a suitable example to specify the impact of the additional uncertainty introduced by damage function calculations, we found two problems with the existing studies. One, investigations neglect possible but unproven effects. Shrader-Frechette (1996) calls this effect *framing uncertainty*. She argues that there is a difference between the *truth or falsity of a scientific hypothesis* (the concern of scientists) and the *acceptability of risk decisions* with regards to environmental impacts. Scientists are interested in minimizing false positives (type I errors) rather than false negatives (type II errors). "In situations of uncertainty, scientists
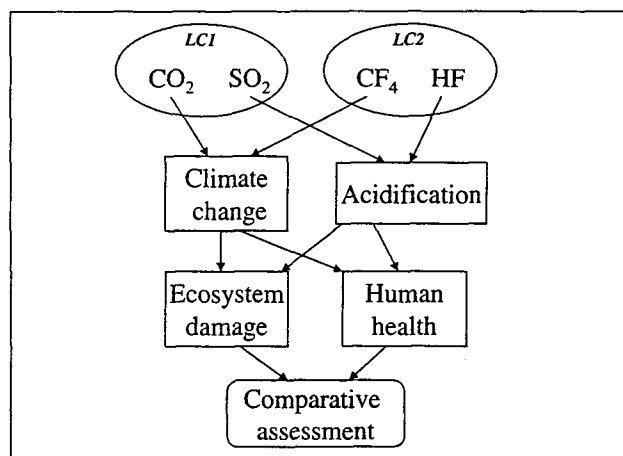
Fig. 2: The uncertainty in our knowledge of different steps in the impact chain differs significantly. The largest uncertainty exists in the connection between increased infrared absorption and changes in weather patterns

Fig. 3: A comparison of two life-cycles (LC1, LC2) may be conclusive at the midpoint level but result in overlapping probability distribution at the endpoint level because of common uncertainties about how climate change and acidification affect the endpoints

place the greater burden of proof on the person who postulates some, rather than no, effect." The result is a tendency to underestimate risks (Shrader-Frechette 1996).[4]

The second problem is the well-documented tendency by both scientists and lay people to underestimate uncertainty (Morgan and Henrion 1990, Shlyakhter et al. 1994). Based on our own experience with uncertainty analysis, we view the reported uncertainties with suspicion. To adjust for the overconfidence of experts, methods such as that proposed by Shlyakhter et al. (1994) can be used. Another consequence of the tendency to underestimate uncertainties, however, is that people are not used to the large uncertainties that exist in reality. It is not clear how they will respond to a full quantification of uncertainty.

The current damage models represent worthwhile attempts to address the difficult question about the absolute environmental impacts of products. Their approaches deserve to be pursued further. Given the problems with the existing methods as well as the principal difficulties regarding the complete accounting for all relevant impacts and the treatment of uncertainties in the analysis, we think it would be unwise to abandon the environmental themes approach. Instead, in the next section we would like to suggest a way in which some to the results of damage modeling could be used to assist the valuation step in the environmental themes approach.

4 From Indicators to Values: the means-ends objectives network

In the first part of this paper (section 4), we have described the means-ends objectives network as a decision-analytic approach towards establishing a connection between the intermediate 'means objectives' and the fundamental 'ends objectives.' The 'judgment about facts' (Keeney 1992) necessary to establish the means-ends objectives network needs to start with a description of these facts. The additional evidence utilized by endpoint methods is clearly relevant for deciding about the importance of different category indicators. A judgment about these facts, however, should not only be based on the numerical results of the midpoint-to-endpoint calculations but also take into account the quality of the underlying evidence, the equity of the distribution of effects in society, and whether risks are imposed or accepted voluntarily.

What we are suggesting is hence a new approach to valuation which does not merely ask individuals or groups about their preference regarding different environmental impacts, but which uses quantitative and qualitative information to describe what we know about the possible or likely effects related to the impact categories. We think the means-ends objectives network offers a good conceptual basis for utilizing the evidence about damages in the environmental themes approach.

5 Conclusions

Life-cycle assessment can be described as a problem of decision analysis. This offers an alternative terminology, as displayed in Table 1, which in itself is not yet a benefit, as there is already an abundance of terminology in LCA. The benefits arise, however, from the access to a rich literature on decision making that is relevant to LCA. This literature is of interest in at least three areas. The first is problem structuring, explored in this paper. The second is methods to trade-off competing objectives, useful for the weighting process. These methods of preference elicitation have been explored by Finnveden et al. (2001). The third area is the evaluation of the effectiveness of decision support methods and computer tools, yet largely unexplored in LCA (Montazemi et al. 1996). The decision analytic framework reconstitutes the characterization step of LCA as the construction of attributes. Attributes are constructed to reflect specific objectives or concerns. The impact web serves as a guide to the design of attributes. Often it is convenient to use scientific models that represent at least part of the causal chain from stressors to consequences. In this case, attributes will have a physical interpretation. The decision analytic framework also provides a more detailed guidance to valuation, or the trade-off among objectives. The means-ends objectives network relates attributes (impact indicators) to fundamental objective or safeguard subjects. Factual, scientific information can be important to better understand this connection. Estimates of the magnitude of expected environmental impacts provided damage functions should be included, together with more qualitative considerations, in the valuation step.

The key difference between environmental themes approaches and damage function approaches lies not in their depth of analysis, but in the factual truth claims embodied in the chosen indicator. The economic damage indicator for climate change (Hammitt et al. 1996) has the same depth of analysis as the calculations of the human health and ecosystem damage embodied in EPS or the EcoIndicator 99. This information is only used to assess the relative importance of different greenhouse gases, however, not the absolute resulting damage e.g. from changes in disease vectors or temperature extremes. Given the unpredictable consequences of climate change and many relevant qualitative considerations that are only insufficiently (or not at all) captured in integrated assessment models of climate change impacts, it may be wiser to leave the ultimate evaluation of the importance of climate change to human judgment. Risk perception studies have shown that individuals do not accept expert evaluations of risk in terms of probability and consequences, especially when unfamiliar or potentially catastrophic impacts are involved (Stern and Fineberg 1996). Such important judgments should be debated as judgments, not as matters of analytical methods.

We have developed criteria for the grouping of stressors and the construction of attributes. For the construction of attributes, we have suggested that the LCA criterion of 'environmental relevance' can be more exactly described as the relevance of the information included in a characterization method and validity of the way it is included, reflecting our understanding of the cause-consequence relationship. In addition, we suggest that good enough data needs to be available that an analytical refinement indeed adds more information than noise. The

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[4] This is also the case in LCA-related studies. Assessments of climate change, e.g. those part of the ExternE project (Eyre et al. 1999), often neglect the expected far-ranging effects on ecosystems because their impact on human welfare is difficult to predict. The Eco-Indicator 99 (Goedkoop and Spriensma 1999) includes only carcinogenic and respiratory health effects of toxic chemicals because dose-response curves are unavailable for other toxic effects. LCIs often neglect processes for which no data was found.

criterion is inspired by the decision-analytic concept of value-of-information. These criteria serve not only as a guidance, they can be used to formulate arguments about the merit of competing impact assessment methods. The development of such criteria enables a more systematic design and selection of impact assessment methods and may especially be useful for method development and standardization efforts like ISO and the emerging UNEP/SETAC Life Cycle Initiative.

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